N94-34978

PREDICTION OF UNSTEADY AIRFOIL FLOWS AT LARGE ANGLES OF INCIDENCE

by

Tuncer Cebeci* and H. M. Jang** and H. H. Chen†

Aerospace Engineering Department

California State University, Long Beach

Abstract

The effect of unsteady motion of an airfoil on its stall behavior is of considerable interest to many practical applications including the blades of helicopter rotors and of axial compressors and turbines. Experiments with oscillating airfoils, for example, have shown that the flow can remain attached for angles of attack greater than those which would cause stall to occur in a stationary system. This result appears to stem from the formation of a vortex close to the surface of the airfoil which continues to provide lift. It is also evident that the onset of dynamic stall depends strongly on the airfoil section and as a result great care is required in the development of a calculation method which will accurately predict this behavior.

In principle, the prediction of dynamic stall can be accomplished by solving the Reynolds-averaged Navier-Stokes equations or their reduced forms. A turbulence model is required and is presumed, with reasonable supporting evidence to be uninfluenced by the imposed unsteadiness. Several papers have been prepared with calculations of this type and involve the solution of equations with two diffusion terms as well as parabolized forms and thin-layer approximations. An alternative is to make use of interactive boundary-layer

---

*Professor and Chairman.

**Research Associate.

†Assistant Professor.

0280h

theory whereby inviscid and boundary-layer equations are solved and allowed to influence each other by an iterative scheme.

Extensive investigations with an interactive approach have been reported by Cebeci et al.[1] and show that the incompressible flow and performance characteristics of airfoils can be predicted accurately and efficiently for high and low Reynolds numbers and for a range of angles of attack up to and including stall. At incidence angles higher than stall, however, this procedure, was unable to predict the airfoil performance due to relatively large regions of flow separation on the surface and in the wake. Near stall, the value of the trailing edge displacement thickness approached 10% of the chord and the numerical method could not provide converged solutions. The predictions of this interactive boundary-layer are similar to those obtained from solutions of thin-layer Navier-Stokes by the ARC-2D method for angles of attack up to and including stall. It has been shown in Ref. 1 that the interactive flow calculations without the wake effect and for angles of attack greater than that of stall, yielded lift coefficients which increased with incidence angle almost in the same way as those computed with the thin-layer Navier-Stokes approach with the wake effect included. When the wake effect was included in the interactive boundary-layer calculations, the results agreed more closely with measurements but could not be extended beyond the stall angle.

More recently, the interactive method has been improved to permit calculations for angles of attack greater than that of stall and the results have been shown to have the correct behavior. To achieve this, modifications were made to the iterative procedure and to the method of calculating the wake. These improvements are described in Ref. 2 and are necessary where results are required at angles of attack corresponding to stall and post stall.

The interactive boundary-layer method for steady flows has also been extended to study the laminar separation and reattachment near the leading edge of a thin oscillating airfoil[3], but the calculation of flow over practical airfoils involves laminar and turbulent flows and the inclusion of the upstream influence of the wake requires careful step-by-step development and evaluation, as has been done for steady flows. The use of a quasi-steady approach to unsteady flows represents an essential building block in a progression towards an interactive calculation method which solves unsteady equations even though the latter is likely to represent a much wider range of oscillation frequencies. The extent of the differences can be quantified only by comparing results from both.

Our presentation will describe the extension of the steady interactive boundary-layer method of Cebeci et al.[1] to unsteady flows over practical airfoils subject to a ramp-type motion. The method makes use of the unsteady panel method developed by Platzer and his student, Teng[4], and is able to compute flows with large regions of flow separation. By solving the quasi-steady and unsteady boundary-layer equations in an interactive method, the quasi-steady method will be assessed over a range of angles of attack and frequency in terms of convenience, accuracy, and the computational cost. The calculations will encompass airfoil and wake flows at angles of attack close to the start of the dynamic stall and will provide insight into the development of dynamic stall as a result of the trailing edge separation.

References

1. Cebeci, T., Clark, R.W., Chang, K.C., Halsey, N.D. and Lee, K.: Airfoils with Separation and the Resulting Wakes. J. Fluid Mech., Vol. 173, pp. 323-347, 1986.

2. Cebeci, T., Jau, J., Vitiello, D. and Chang, K.C.: Prediction of Post-Stall Flows on Airfoils. In Numerical and Physical Aspects of Aerodynamic Flows, IV (ed. T. Cebeci), Springer-Verlag, N.Y., 1990.

3. Cebeci, T., Khattab, A.A. and Schimke, S.M.: Separation and Reattachment Near the Leading Edge of a Thin Oscillating Airfoil. J. Fluid Mech., Vol. 188, 1988, pp. 253-274.

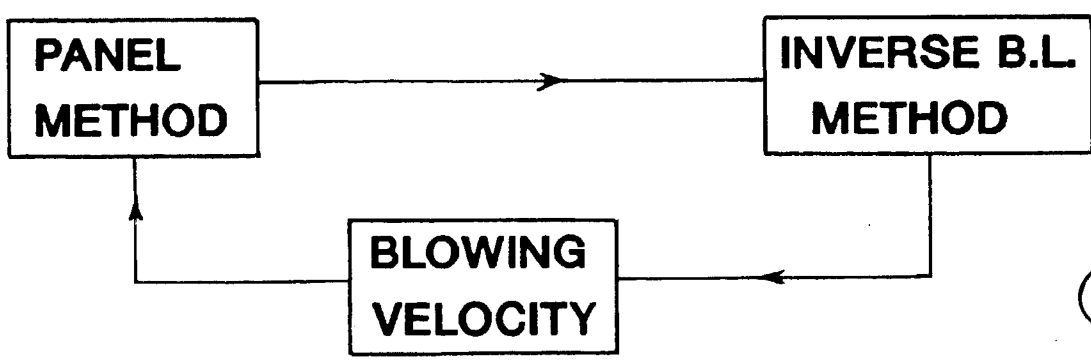
4. Teng, N.G.: The Development of a Computer Code for the Numerical Solution of Unsteady Inviscid, and Incompressible Flow Over an Airfoil. M.S. Thesis, Naval Postgraduate School, Monterey, CA, 1987.

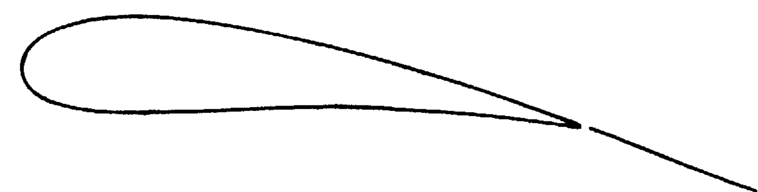
PURPOSE

TO DEVELOP AN INTERACTIVE BOUNDARY-LAYER (IBL) METHOD CAPABLE OF COMPUTING UNSTEADY FLOWS ON AIRFOILS INCLUDING DYNAMIC STALL.

APPROACH

EXTENSION OF AN ACCURATE METHOD FOR COMPUTING STALL AND POST STALL ON AIRFOILS IN STEADY FLOWS.





CALCULATIONS ON THE AIRFOIL
AND IN THE WAKE

STEPS IN THE DEVELOPMENT OF THE PROCEDURE, 1

1. UNSTEADY PANEL METHOD + QUASI-STEADY BOUNDARY-LAYER METHOD

2. UNSTEADY PANEL METHOD + UNSTEADY BOUNDARY-LAYER METHOD

PANEL METHOD WITH AND WITHOUT VISCOUS EFFECTS

- EXTENSION OF THE HESS-SMITH PANEL METHOD TO UNSTEADY FLOWS, BY M.F. PLATZER AND HIS STUDENT TENG.
- INCLUSION OF VISCOUS EFFECTS, BY H.M. JANG.

STEPS IN THE DEVELOPMENT OF THE PROCEDURE, 2

UNSTEADY BOUNDARY-LAYER METHOD

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{\partial u_e}{\partial t} + u_e\frac{\partial u_e}{\partial x} + \frac{\partial}{\partial y}\left[(\nu + \varepsilon_m)\frac{\partial u}{\partial y}\right]$$

$$y = 0: \qquad u = v = 0$$

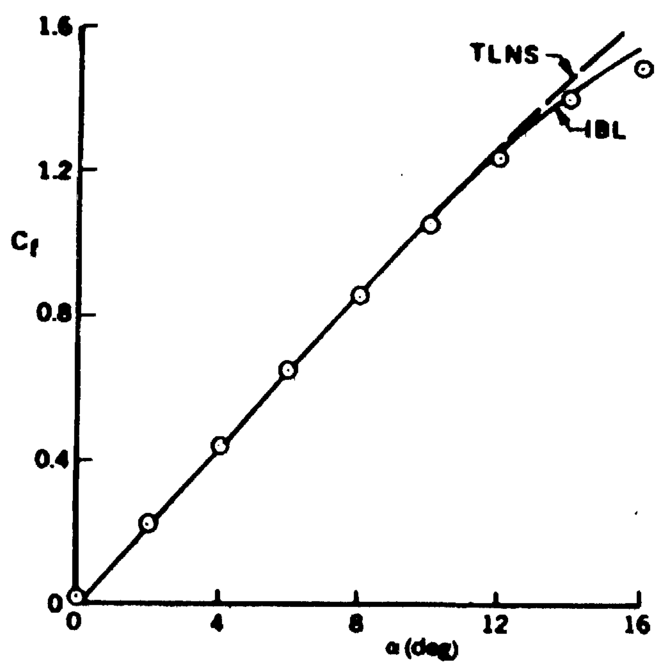
$$y = \delta: \qquad u_e(x) = u_e^o(x) + \delta u_e(x)$$

$$\delta u_e(x) = \frac{1}{\pi}\int_{x_a}^{x_b} \frac{d}{d\sigma}(u_e\delta \times)\frac{d\sigma}{x - \sigma}$$

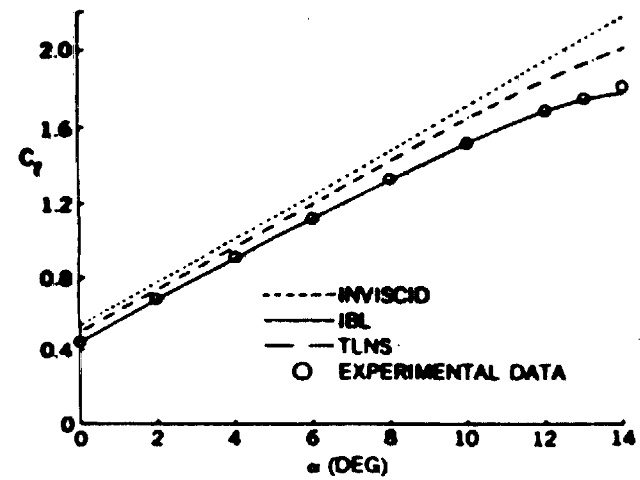
SOME FEATURES OF THE METHOD FOR STEADY FLOWS, 1

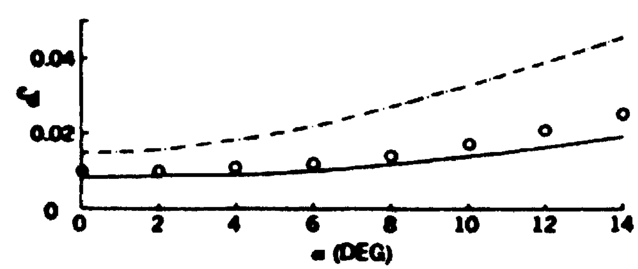
1. COMPARISONS WITH NS SOLUTIONS AND WITH EXPERIMENT

NACA 0012 AIRFOIL, $R_c = 6 \times 10^6$



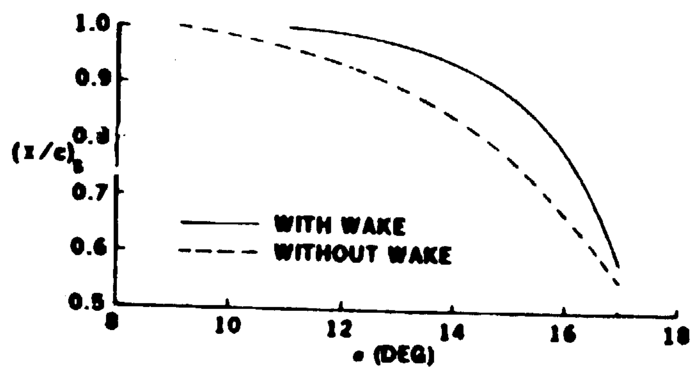
GA(W)-2, $R_c = 4.3 \times 10^6$

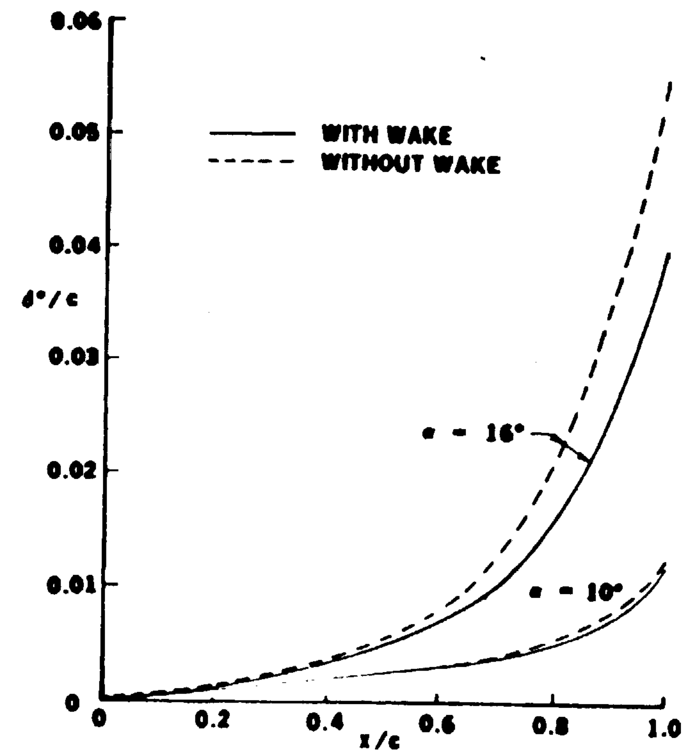




SOME FEATURES OF THE METHOD FOR STEADY FLOWS, 2

2. EFFECT OF WAKE

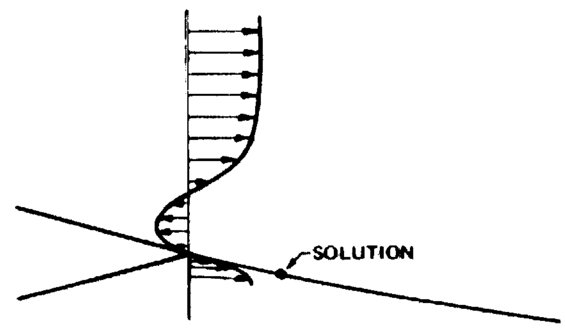




SOME FEATURES OF THE METHOD FOR STEADY FLOWS, 3

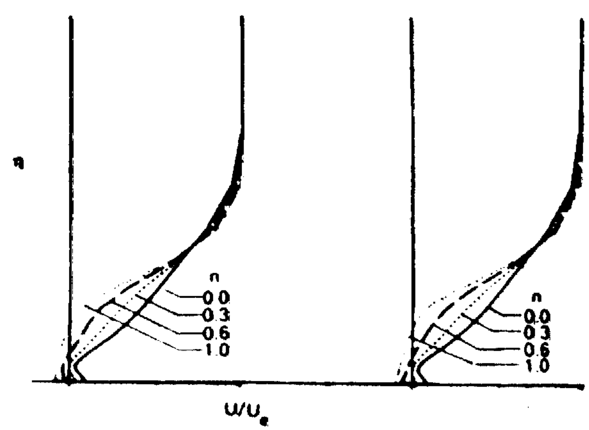
3. **RECENT WORK AND IMPROVEMENTS FOR POST-STALL FLOWS**

- **SOLUTIONS ARE SENSITIVE TO**
  - **TRANSITION AT HIGH ANGLES OF ATTACK, AND**
  - **LARGE FLOW SEPARATION,ESPECIALLY IN WAKE**
    i.e. NEAR STALL, AT THE TRAILING EDGE



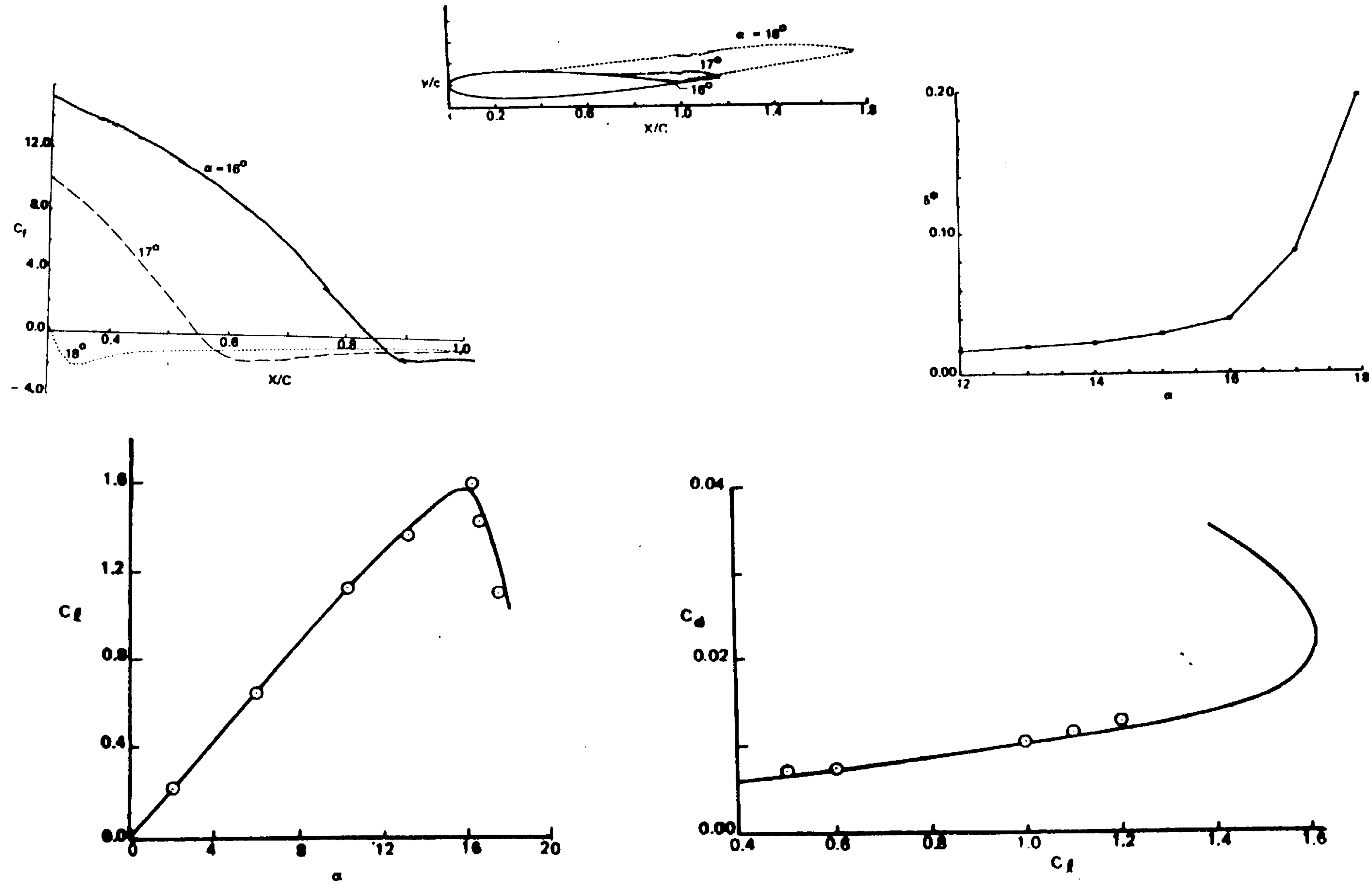
CONTINUATION METHOD

$u = u_{ref} + n(u_e - u_{ref}) \quad n = 0, 0.1, 0.2, \ldots, 1.0$



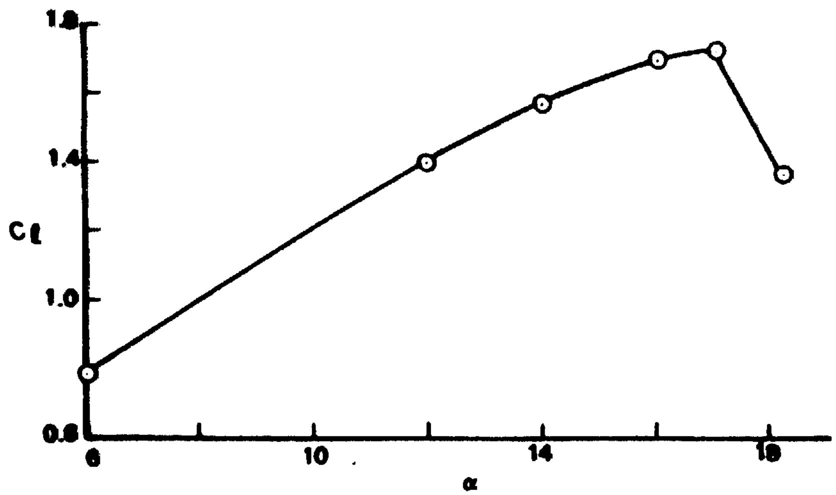
SOME FEATURES OF THE METHOD FOR STEADY FLOWS, 4

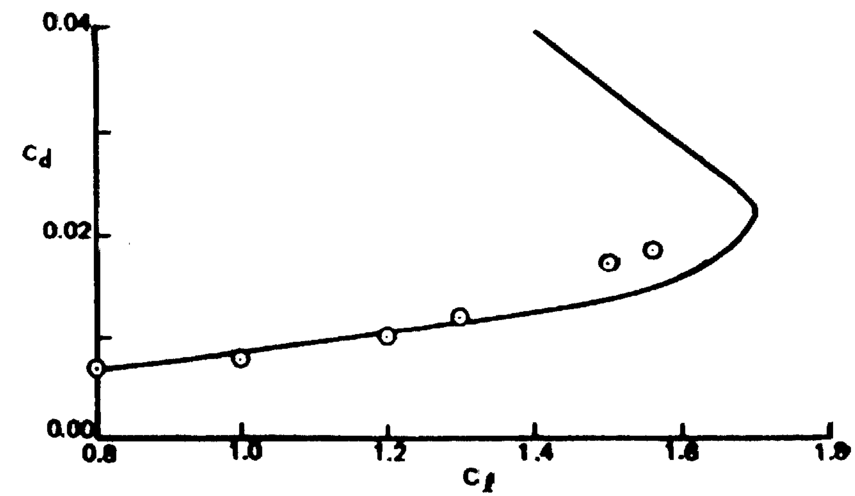
NACA 0012 AIRFOIL, $R_c = 6 \times 10^6$



SOME FEATURES OF THE METHOD FOR STEADY FLOWS, 5

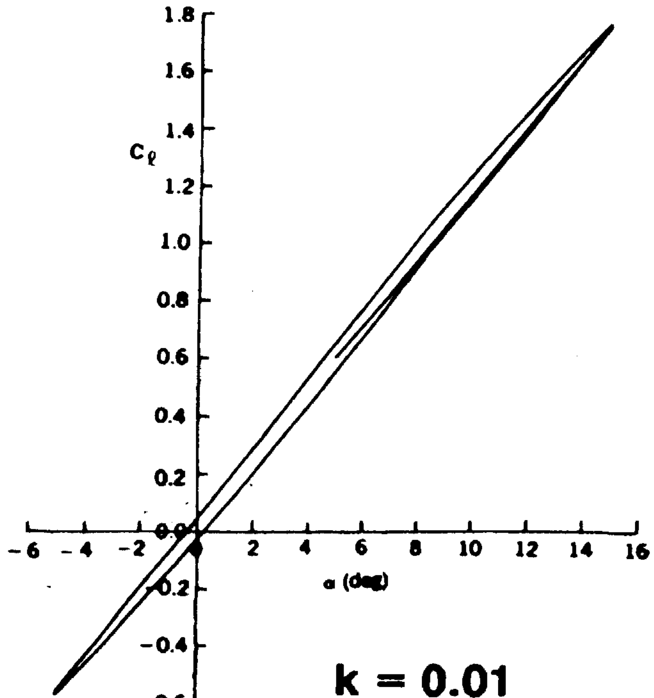
NACA 23012 AIRFOIL, $R_c = 6 \times 10^6$



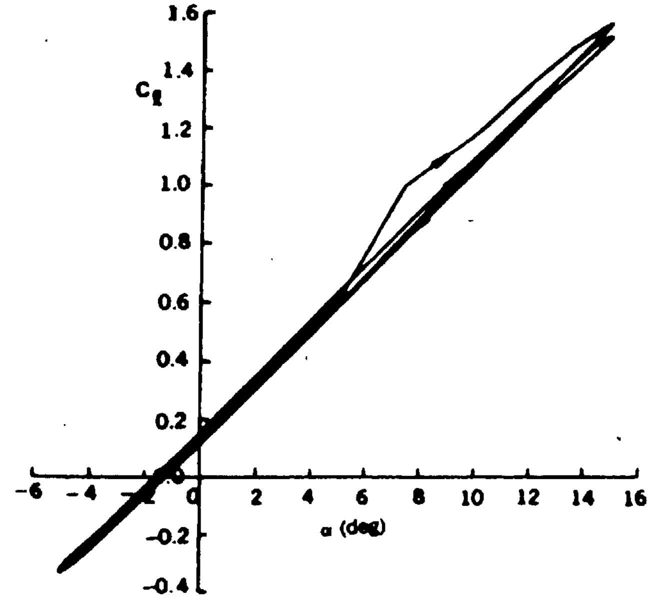


RESULTS FOR $\alpha = 5 + 10 \sin \omega t$

TRANSIENT EFFECTS

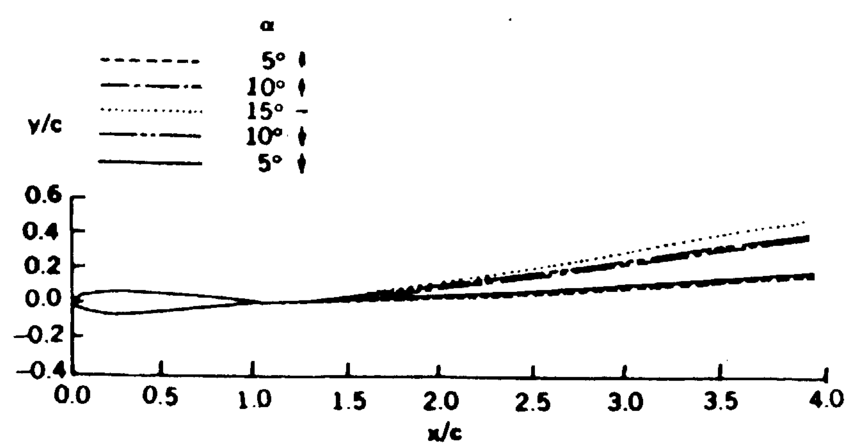


k = 0.01



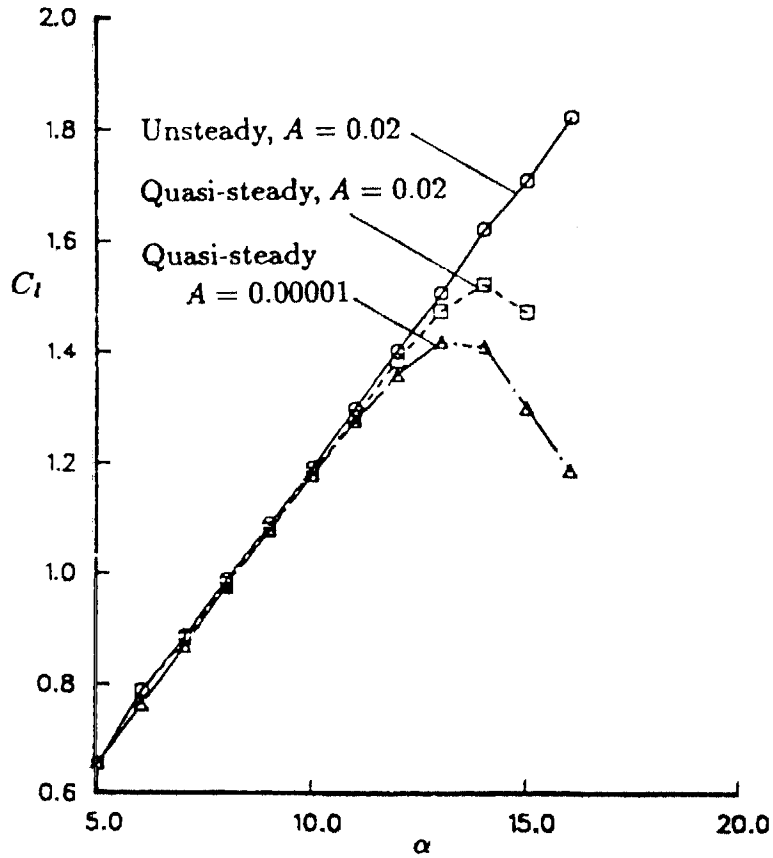
k = 0.15

VARIATION OF THE WAKE LOCATION FOR k = 0.01

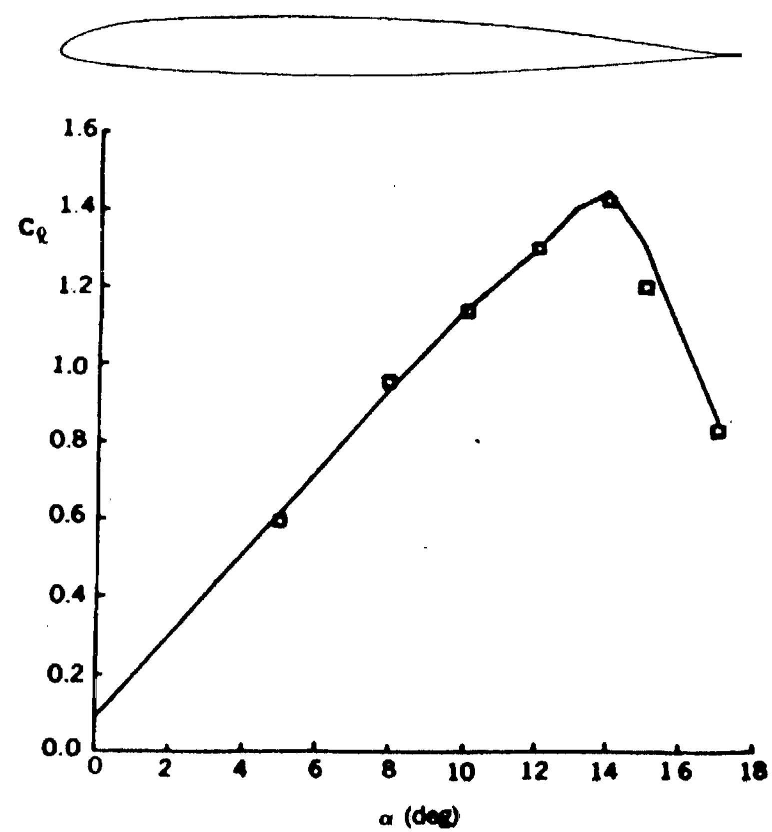


EFFECT OF PITCH RATE ON THE LIFT COEFFICIENT OF THE SSC-A09 AIRFOIL

$$R_c = 2 \times 10^6$$



STEADY STATE



EFFECTS OF PITCH RATE ON THE DISPLACEMENT THICKNESS DISTRIBUTION OF THE SSC-A09 AIRFOIL

$$R_c = 2 \times 10^6$$